PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 : G01V 3/24

A1

(11) International Publication Number: WO 00/65380

(43) International Publication Date: 2 November 2000 (02.11.00)

(21) International Application Number: PCT/EP00/03749

(22) International Filing Date: 21 April 2000 (21.04.00)

(30) Priority Data:
99/05341 28 April 1999 (28.04.99) FR

(71) Applicant *(for all designated States except CA FR GB)*: SCHLUMBERGER TECHNOLOGY B.V. [NL/NL]; Parkstraat 83-89, NL-2514 JG The Hague (NL).

(71) Applicant *(for FR only)*: SERVICES PETROLIERS SCHLUMBERGER [FR/FR]; 42, rue Saint Dominique, F-75007 Paris (FR).

(71) Applicant *(for CA only)*: SCHLUMBERGER CANADA LIMITED [CA/CA]; 24th Floor, Monenco Place, 801 6th Avenue, S.W., Calgary, Alberta T2P 3W2 (CA).

(71) Applicant *(for GB only)*: SCHLUMBERGER HOLDINGS LIMITED [-/-]; P.O. Box 71, Craigmuir Chambers, Road Town, Tortola (VG).

(72) Inventor: GOUNOT, Marie-Therese; 2, route de la Borde, F-78110 Le Vesinet (FR).

(74) Agent: MENES, Catherine; Etudes & Productions Schlumberger, 26, rue de la Cavée, B.P. 202, F-92142 Clamart Cedex (FR).

(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
With international search report.

(54) Title: A METHOD AND APPARATUS FOR DETERMINING THE RESISTIVITY OF A FORMATION THROUGH WHICH A CASED WELL PASSES

(57) Abstract

The invention relates to a method of surveying the resistivity of a geological formation through which a borehole provided with metal casing passes, in which method a leakage current is caused to leak into said formation outside the casing, and said leakage current is determined on a casing section at a certain level, the leakage current being indicative of the resistivity of the formation. According to a characteristic of the invention, the resistivity is determined on the basis of the leakage current by applying a factor that depends on the distance $\underline{z}$ between said level and the surface.

A METHOD AND APPARATUS FOR DETERMINING THE RESISTIVITY OF A FORMATION THROUGH WHICH A CASED WELL PASSES

The invention relates to determining the resistivity of geological formations through which a well provided with metal casing passes.

The importance of resistivity logging for oil prospecting is well known. It is known that the resistivity of a formation depends essentially on the fluid that it contains. A formation containing salt water, which is conductive, has resistivity that is much lower than a formation filled with hydrocarbons, and therefore resistivity measurements are of irreplaceable value for locating hydrocarbon deposits. Resistivity logging has been performed widely and for many years, in particular by means of apparatus having electrodes, but existing techniques have a field of application that is limited to wells that are not cased, or "open holes" as they are referred to in oil industry terminology. The presence in the well of metal casing, which has resistivity that is minute compared with typical values for geological formations (about 2 x 10^{-7} ohm.m for steel casing compared with values in the range 1 ohm.m to 1000 ohm.m for a formation), represents a considerable barrier to sending electrical currents into the formations surrounding the casing. As a result, in particular, it is not possible to obtain resistivity measurements in wells that are in production, since such wells are provided with casing.

It would therefore be very advantageous to make it possible to measure resistivity in sections of cased wells. Such measurements, taken in a well in production at the level of the deposit, would make it possible to locate the water-hydrocarbon interfaces and thus to monitor how the positions of such interfaces vary over time, so as to monitor the behavior of the hydrocarbon reservoir and so as to optimize extraction therefrom. It would also be possible to obtain a resistivity measurement in a well (or a well section) for which no measurements were taken before the casing was put into place, in particular in order to supplement knowledge of the reservoir, and optionally to detect productive layers that were not located initially.

Proposals have been made on this subject in the literature. The basic measurement principle presented in Patent Document US 2 459 196 consists in causing a current to flow along the casing under conditions such that current leaks out or is lost to the formation. Such loss is a function of the resistivity of the formation: the more the formation is conductive, the greater the current loss. By measuring current loss, it is possible to determine the resistivity of the formation. Current loss can be evaluated by measuring the voltage drop between electrodes placed at different depths in the well. Patent Document US 2 729 784 describes a measurement method

using two pairs of measurement electrodes a,b and b,c spaced apart along the casing, the electrodes a and c being in principle equidistant from the electrode b. Current electrodes are placed on either side of the measurement electrodes so as to inject currents into the casing in opposite directions. A feedback loop servo-controls the injected current so as to put the external measurement electrodes at the same potential, so as to cancel out the effect of the resistance of the casing varying in the sections (a,b) and (b,c) as defined by the measurement electrodes. A value for the leakage current at the level of the central electrode b is obtained by measuring the voltage drop across each of the pairs of electrodes a,b and b,c, and by taking the difference between the voltage drops, which difference is stated to be proportional to the leakage current.

French Patent Document 2 207 278 provides the use of three measurement electrodes spaced apart uniformly as in Patent Document US 2 729 784 for measuring current leakage, and it describes a method in two steps: a first step for measuring the resistance of the casing section defined by the external measurement electrodes, during which step current is caused to flow along the casing so that there is no leakage into the formation; and a second step during which current can leak to the formation. For that purpose, a current injection system is provided that comprises one emission electrode and two return electrodes, a near one of the measurement electrodes being active during the first step, and the other measurement electrode being situated at the surface and being active during the second step.

Patent Document US 4 796 186 describes a method in two steps of the same type as the method described in above-mentioned French Patent Document 2 207 278, and using the same electrode configuration. It provides a circuit for cancelling out the effect of resistance varying between the two sections of casing. That circuit comprises amplifiers connected to each pair of measurement electrodes so as to deliver respective voltage drops at their outputs. One of the amplifiers is a variable-gain amplifier, its gain being adjusted during the first step so as to cancel out the difference between the outputs of the amplifiers. Patent Document US 4 820 989 describes an identical compensation technique.

Using Ohm's law, in order to determine the resistivity of the formation, in addition to knowing the leakage current as measured using one of the methods indicated, it is also necessary to know the potential difference relative to infinity of the casing at the measurement level. In the above-mentioned documents, that potential difference is measured by means of a reference electrode situated at the surface, and at a sufficient distance from the above-mentioned surface return electrode.

The use of a reference electrode suffers from operational drawbacks. The corresponding measurement must be taken separately from the above-mentioned

measurements, and it thus represents an additional step which increases the total duration of the operations. It also represents a source of error, it being possible for the potential of the reference electrode to be affected by various phenomena. Proposals have been made to omit such a reference electrode. Patent Document US 5 510 712 proposes applying currents to the casing at two places that are spaced apart in the longitudinal direction. Similarly, Patent Document US 5 543 715 proposes an additional current electrode. Those proposals suffer from the drawback of complicating the measurement apparatus and in particular of increasing the length thereof.

In one aspect, the invention provides a method of surveying the resistivity of a geological formation through which a borehole provided with metal casing passes, in which method a leakage current is caused to leak into said formation outside the casing, and said leakage current is determined on a casing section at a certain level, the leakage current being indicative of the resistivity of the formation , said method being characterized by the fact that the resistivity is determined on the basis of the leakage current by applying a factor that depends on the distance $\underline{z}$ between said level and the surface.

In a preferred implementation, said factor takes into account the length of the casing.

The invention will be well understood on reading the following description given with reference to the accompanying drawings, in which:

Figure 1 summarizes the principle of measuring resistivity in a cased well;

Figure 2 diagrammatically shows downhole apparatus designed to implement said principle;

Figures 3A, 3B, and 3C show different operating states of the apparatus shown in Figure 2; and

Figure 4 shows, by way of example, a result obtained for the resistivity of a formation by applying the method described below to determine the potential of the casing.

The principle of measuring resistivity in a cased well consists in causing current to flow along the casing with a return that is remote, so as to enable current to leak towards the geological formations through which the well passes, and to evaluate the leakage current: at any given level down the well, the higher the conductivity of the formation surrounding the well at said level, the higher the leakage current. This can be expressed in mathematical terms by an exponentially decreasing relationship for the current flowing through the casing, with a rate of decrease, at any given level being a function of the ratio of formation resistivity Rt to casing resistivity Rc.

The diagram in Figure 1 shows a section of a well 10 having an axis X-X' and provided with metal casing 11. The desired level (or depth) at which the measurement is to be taken is referenced b. Consideration is given to a section of casing (a,c) extending on either side of the level b. If a current flows through the casing with a return that is remote (i.e. at surface level), the loss of current to the formation can be expressed in electrical circuit diagram terms by a shunt being placed between the level b of the casing and infinity. The resistance of the shunt is representative of the resistivity Rt of the formation at the level of the electrode b. Using Ohm's law, it is thus possible to write:

$Rt = k(Vb,\infty/Ifor)$ [1]

where k is a geometric constant which can be determined by calibration measurements, Vb,∞ is the potential of the casing at level b with a reference at infinity, and Ifor is the leakage current at level b.

By approximating a discrete variation, it is possible to describe a loss of current at level b as a difference between the input current at level b and the output current. The leakage current Ifor is thus expressed as the difference between the currents Iab and Ibc (which are assumed to be constant) flowing respectively in the casing sections (a,b) and (b,c):

$Ifor = Iab - Ibc$ [2]

or

$Ifor = Vab/Rab - Vbc/Rbc$ [2']

where Vab and Rbc are the potential drops respectively along the section (a,b) and along the section (b,c) of the casing, and Rab and Rbc are the values of the resistance respectively of the section ab and of the section bc of the casing. It is assumed initially that the current applied to the casing is DC.

In view of the ratio between the resistivity of the casing and the usual resistivity values of the formations, which ratio lies in the range 10^7 to 10^{10}, the current loss over a length that corresponds to a resolution that is acceptable for a formation resistance measurement, e.g. in the range 30 cm to 1 m, is very small. The difference between the potential drops Vab and Vbc that can be ascribed to the current loss is therefore normally a very small quantity. As a result, uncertainties, even small uncertainties, concerning the terms of the difference have a major influence. For various reasons (localized corrosion, non-uniformness of the casing material, or variation in thickness), the resistance values per unit length of the casing sections (a,b) and (b,c) can differ from the value corresponding to the nominal characteristics of the casing, and above all can be different from each other. An uncertainty also affects the lengths of the casing sections (a,b) and (b,c) because said lengths depend on the

positions of the contact points at which the electrodes are in contact with the casing, which positions are known only with relatively poor accuracy.

Figure 2 diagrammatically shows apparatus for implementing the above-described principle.

The apparatus comprises a sonde 12 suitable for being moved in an oil borehole 10 provided with casing 11, and it is suspended from the end of an electrical cable 13 which connects it to surface equipment 14 comprising data acquisition and processing means and an electrical power supply 16. The sonde 12 is provided with three measurement electrodes a, b, and c which can be placed in contact with the casing, thereby defining casing sections (a,b) and (b,c) of length lying appropriately in the range 40 cm to 80 cm. In the embodiment shown, the electrodes a, b, and c are mounted on arms 17 hinged to the sonde 12. By means of mechanisms of known type that it is unnecessary to describe in detail herein, these arms may be swung out from the sonde so as to put the electrodes in contact with the casing, and then put back in the retracted position once the measurements have been finished. The electrodes are designed so that, once they are in contact with the casing, their positions remain as stationary as possible, and so that electrical contact with the casing is optimum.

A sonde of this type may be made on the basis of the instrument used commercially by Schlumberger for the "CPET" service, as indicated in Patent Document US 5 563 514. That instrument, which is designed to evaluate the cathodic protection of casing and the state of corrosion thereof, is provided with twelve measurement electrodes distributed over four levels spaced apart in the longitudinal direction, the distance between levels being about 60 cm, and the three electrodes on each level being disposed symmetrically about the axis of the instrument, i.e. with angular spacing of 120° between adjacent electrodes.

To measure formation resistivity, three electrodes a, b, c suffice. But it is possible to use a larger number of levels, e.g., as in the above-mentioned instrument, four levels that can form two groups of three consecutive levels, so as to acquire more information and so as to take measurements corresponding to two different depths simultaneously. In such cases, each set of three consecutive electrodes is associated with the processing circuits described below. As regards the number of electrodes per level, a single electrode suffices.

The sonde is further provided with current electrodes disposed on either side of the electrodes a and c, namely a top electrode In1 and a bottom electrode In2, at distances from the electrodes a and c that may be of the same order or a little greater than the distance between the electrodes a and c, e.g. a few meters. Insulating fittings 18, such as fittings of the AH169 type commonly used by Schlumberger, are placed

on either side of the central portion of the sonde, which central portion carries measurement electrodes a, b, and c, so as to isolate said central portion from the current electrodes In1 and In2. The current electrodes In1 and In2 may be made in the manner of conventional centralizers for cased wells. The wheels normally provided on such centralizers as elements that come into contact with the casing are then replaced by elements serving as current electrodes, and electrical conductors are provided for connecting to the electrode-forming elements.

The apparatus is also provided with a remote return electrode In3 preferably placed at surface level, at the well head (if the well is deep enough) or at some distance from the well head, and with means for feeding the current electrodes so as to establish the various circuits described below with reference to Figures 3A to 3C. The means comprise the above-mentioned surface current source 16, and, depending on the case, an additional source situated in the sonde, as well as suitable switching circuits.

The diagrams given in Figures 3A to 3C show measurement steps corresponding to the various current-passing circuits that can be established by means of the above-described apparatus. As explained below, two (or three) such steps suffice to obtain the desired results.

These diagrams show a processing circuit including amplifiers Dab and Dbc whose inputs are connected respectively to the electrodes a and b, and to the electrodes b and c, and which deliver at their outputs the voltage drops Vab and Vbc on the casing sections defined by the electrodes, and an amplifier Dabc connected to the amplifiers Dab and Dbc and delivering at its output the difference Vabc between the voltage drops Vab and Vbc. This circuit is preferably situated in the downhole sonde 12. It is supplemented by calculation means preferably belonging to the data acquisition and processing means 15 of the surface equipment, which calculation means receive the voltages from the processing circuit and the other pertinent data and deliver the resistivity values Rt. The data is transmitted conventionally via the cable 13 in digital form, an analog-to-digital converter (not shown) being provided in the sonde 12 and connected to the processing circuit.

The step shown in Figure 3A calibrates the measurement system formed by the measurement electrodes a, b, and c and the casing sections 11 that they define.

In this step, a current is applied to the casing by means of the circuit formed by In1 as injection electrode and by In2 as near return electrode, by placing the switching circuits in the appropriate position. In this way, the current substantially does not penetrate into the formation surrounding the well. The current is preferably low-

frequency AC, e.g. having a frequency in the range 1 Hz to 5 Hz, but the reasoning below assumes that the current is DC.

With the applied current being referenced It, the outlet voltages of the amplifiers are as follows:

$Vab_C = Rab.It$[3]

$Vbc_C = Rbc.It$[3']

$Vabc_C = (Rab - Rbc).It$ [3"]

The step shown in Figure 3B uses a current-application circuit made up of a top electrode In1 and of the remote electrode In3, the applied current being of the same type as in the first step, namely AC of the same frequency. Under these conditions, current leakage is produced as described above with reference to Figure 1, which leakage is a function of the resistivity of the formation at the level of the electrode b. With the current flowing downwards through the casing sections (a,b) and (b,c) being referenced Id, and the leakage current being referenced Ifor as above, the output voltages of the amplifiers are as follows:

$Vab_T = Rab.Id$ [4]

$Vbc_T = Rbc\ (Id - Ifor)$ [4']

$Vabc_T = (Rab - Rbc).Id + Rbc.Ifor$ [4"]

By combining these expressions, it is possible to deduce the leakage current Ifor:

$Ifor = It.[Vabc_T - (Vabc_C.Vab_T/Vab_C)]/(Vab_C - Vabc_C)$ [5]

The step shown in Figure 3C differs from the step in Figure 3B only in that the bottom electrode In3 is used instead of the top electrode In1 to apply current, the return being provided by the surface electrode In3. As in the step in Figure 3B, current therefore leaks to the formation, but the current flows upwards through the casing sections (a,b) and (b,c). This current is referenced Ih and the voltages obtained are referenced Vab_B, Vbc_B, and $Vabc_B$.

It should be noted that, by virtue of the principle of superposition, the current circuit shown in Figure 3A and made up of the electrodes In1 and In2 is equivalent as regards the electrical magnitudes (current and voltage) to the difference between the circuit shown in Figure 3B and the circuit shown in Figure 3C, if the current applied respectively by the electrodes In1 and In2 is the same. Hence symbolically:

CIRCUIT 3A = CIRCUIT 3B - CIRCUIT 3C

The current and voltage values in above expression [5] and corresponding to the step shown in Figure 3A may thus be replaced, in accordance with the invention, with the differences between the corresponding values obtained respectively in the steps shown in Figures 3B and 3C: thus, $Vab_C = Vac_T - Vac_B$, etc. That makes it

possible to replace the step shown in Figure 3A with the step shown in Figure 3C. The advantage of this solution is that the current application circuit is simplified. In this respect, it should be noted that the step shown in Figure 3A requires either a current source in the downhole sonde, or a current source on the surface and connected to two additional strands in the cable 13.

In order to determine the formation resistivity Rt, once the leakage current Ifor has been calculated in this way, there remains the task of determining the potential of the casing relative to a reference at infinity Vb,∞, as explained above. This is performed as described in the above-mentioned literature, by means of a reference electrode which may be placed on the surface, remote from the surface return electrode In3, or preferably situated in the well, e.g. on the insulated cable portion or "bridle" connecting the downhole apparatus to the cable. It is thus possible to measure the potential difference Vbs between the casing at the level of the measurement electrode b and the reference electrode. Using the above-mentioned equation [1], the ratio K.Vbs/Ifor is formed, where K is the above-mentioned constant, so as to deduce the formation resistivity Rt. This measurement of the voltage Vbs cannot be performed simultaneously with the other above-mentioned measurements because of coupling phenomena in the cable.

A method of the invention offers the advantage of avoiding the use of a reference electrode and the additional operation represented by measuring the voltage Vbs, and consists in determining the potential of the casing by calculation. Using Ohm's law, said potential may be obtained as the product of the total applied current multiplied by the resistance of the casing.

In the invention, it is appropriate to apply the following relationship:

$Rt = A(z).Gb.It_{\mathcal{T}}/Ifor$ [6]

in which A(z) is a term which corrects the effect of the proximity of the casing shoe, and it depends on the depth z of the measurement electrode b, Gb is a term which characterizes the geometrical shape and the properties of the casing at the level of the electrode b, and $It_{\mathcal{T}}$ is the total current applied via the top electrode In1 during the step described in Figure 3B.

The measurements to be taken concern the hydrocarbon-producing zones, which are generally situated at a limited distance above the casing shoe. The proximity of the casing shoe amplifies current leakage into the formation because it constitutes a considerable discontinuity for the current flowing down from the electrode In1. Compared with the length characteristic of the above-mentioned exponential decrease, only a short distance is available to this current in which to leak from the casing.

The term A(z) aims to correct this effect.

Specifically, it has been found that a satisfactory correction is obtained by using the following expression for the term A(z):

$A(z) = \arg\sinh \{2z/(l_C - z)\}$ [6']

where l_C is the total length of the casing, which length is known for the borehole in question. The depth z is more exactly the distance from the measurement level b to the surface. It is measured in a manner well known in the field of oilwell logging.

Naturally, other mathematical expressions may be considered, provided that they give a result comparable to that of expression [6'].

The term Gb is defined appropriately by the following relationship:

$Gb = (\pi D_C.h/e).Rab$ [6"]

where D_C is the outside diameter of the casing at the measurement level b, h is the length of the casing section defined by the electrodes a and b, Rab is, as indicated above, the resistance of the casing over the section (a,b) and e is the thickness of the casing at level b.

For the outside diameter D_C, a nominal value is known, and this value is satisfactory. For the thickness e, it is possible, by way of approximation, to use a nominal value deduced from the available nominal values (outside diameter and weight per unit length) and from the density of the steel constituting the casing. However, it is observed that the thickness e can differ from this nominal value, and, in addition, it can vary over time because of corrosion phenomena. It is thus preferable to determine its value at level b as a function of the measurements taken at said level, in view of the fact that the resistance of the casing also depends on its sectional area s ($R = \rho.l/s$), and therefore on the thickness e. For this purpose, the measurement step described above with reference to Figure 3A is used. As appears from relationship [3], the resistance Rab of the casing over the section (a,b) can be determined on the basis of the voltage Vab_C and of the applied current It. The resistivity of the steel at depth z is also determined, as a function of temperature at said depth, and it is measured as is conventional in the field of oilwell logging. A thickness value e(z) specific to level b is deduced therefrom.

As explained above, it is advantageously possible to replace the measurement of Figure 3A with the difference between the measurements of Figures 3B and 3C. This applies to determining Rab. The magnitudes Vab_C and It are then obtained by taking the difference between the corresponding magnitudes in the steps 3B and 3C, it being recalled that the current applied to the casing is the same in both steps.

The corresponding calculation is performed in the above-mentioned calculation means situated in the surface equipment. For this purpose, the calculation means receive all of the pertinent data from the downhole sonde 12 or from surface apparatus for the depth data z. In addition, the values of the parameters involved in the calculation are pre-stored in the calculation means.

Figure 4 gives an example of the results obtained by applying the above-described method for calculating the formation resistivity Rt to the data obtained in a test well. The section surveyed extended from a depth (represented along a horizontal axis) of less than 500 m to a depth of more than 1100 m. The solid-line curve corresponds to the previously-known resistivity values, the dashed-line curve corresponding to applying the above method to data acquired by means of apparatus as described in the present specification. It should be noted that the dashed-line curve coincides almost exactly with the solid-line curve, which shows the effectiveness of the above method.

For reasons of simplification, in the above description it is assumed that the applied current is DC. In fact, AC is used, preferably at a low frequency, lying appropriately in the range 1 Hz to 5 Hz. In view of the reactive effects due to the metal of the casing (skin effect), the casing sections (a,b) and (b,c) are characterized by their complex impedance values Zab, Zbc, in which the resistances Rab and Rbc are the real portions, and the currents flowing through the casing sections (a,b) and (b,c) and the voltages across their terminals are complex magnitudes, each of which includes a component in quadrature relative to the applied current.

The leakage current is then determined by applying above relationship [5] with the complex voltages Vab_C, $Vabc_C$, Vab_T, and $Vabc_T$. A complex leakage current Jfor is thus obtained for which the real portion Re(Jfor) must be determined in order to calculate the formation resistivity Rt.

In accordance with the invention, it is observed that the leakage current Jfor has a constant phase relationship with the current Id (or Ih) flowing through the casing at the level of the electrode b during the step 3B (or, respectively, 3C) over the entire section of the casing, while the current Id (or Ih) is phase-shifted relative to the current applied in the steps 3B, 3C, by a value that varies over the section of the casing, that depends on numerous parameters, and that is therefore difficult to predict, and therefore the component of Jfor that is in phase with the current Id is used to determine the real portion of Jfor.

The complex current Id is obtained on the basis of the measurements of the steps 3A and 3B (it being possible advantageously for the measurements of the step 3A to be obtained by means of the difference between the measurements of step 3B

and the measurements of step 3C, as described above). With the references used above, relationships [3] and [4] become:

$$Vab_C = Zab.It$$

$$Vab_T = Zab.id$$

hence:

$$Id = (Vab_T/Vab_C).It$$

If φ_d is the phase of the current Id relative to the injected current It, and φ_J is the phase of the leakage current Jfor relative to the current It, the real portion of Jfor is determined, in view of the above, by the following relationship:

$$Re(Jfor) = |Jfor| \cos(\varphi_J - \varphi_d)$$

The corresponding processing means are preferably distributed between the downhole sonde 12 and the above-mentioned calculation means situated in the means 15 of the surface equipment. Appropriately, the downhole sonde is provided with circuits delivering the real and imaginary portions of the magnitudes measured, and the above-described calculations are performed by the calculation means situated in the surface equipment.

CLAIMS

1/ A method of surveying the resistivity of a geological formation through which a borehole provided with metal casing passes, in which method a leakage current is caused to leak into said formation outside the casing, and said leakage current is determined on a casing section at a certain level, the leakage current being indicative of the resistivity of the formation, said method being characterized by the fact that the resistivity is determined on the basis of the leakage current by applying a factor that depends on the distance $\underline{z}$ between said level and the surface.

2/ A method according to claim 1, in which said factor comprises a correction term A(z) for correcting the proximity of the casing shoe multiplied by a term Gb characterizing said casing section.

3/ A method according to claim 2, in which said correction term A(z) is of the form arg sinh $\{2z/(l_C - z)\}$, where l_C is the length of the casing.

4/ A method according to claim 2 or 3, in which the term Gb is of the form Gb = $(\pi D_C.h/e)$.Rab, where D_C is the outside diameter of the casing, $\underline{e}$ is the thickness of the casing at this level, $\underline{h}$ is its length, and Rab is the resistance of said casing section.

5/ A method according to any one of claims 1 to 4, in which said casing section is defined by three electrodes $\underline{a}$, $\underline{b}$, $\underline{c}$, applied against the casing in positions spaced apart in the longitudinal direction of the casing, and the leakage current is determined at the level of the middle electrode $\underline{b}$ on the basis of the difference Vabc between the voltages Vab and Vbc measured across the terminals respectively of the electrodes (a,b) and of the electrodes (b,c).

6/ A method according to any one of claims 1 to 5, in which the current applied to the casing is AC, and the component of the leakage current that is in a constant phase relationship with the current flowing through the casing at said level is determined in order to determine the resistivity.

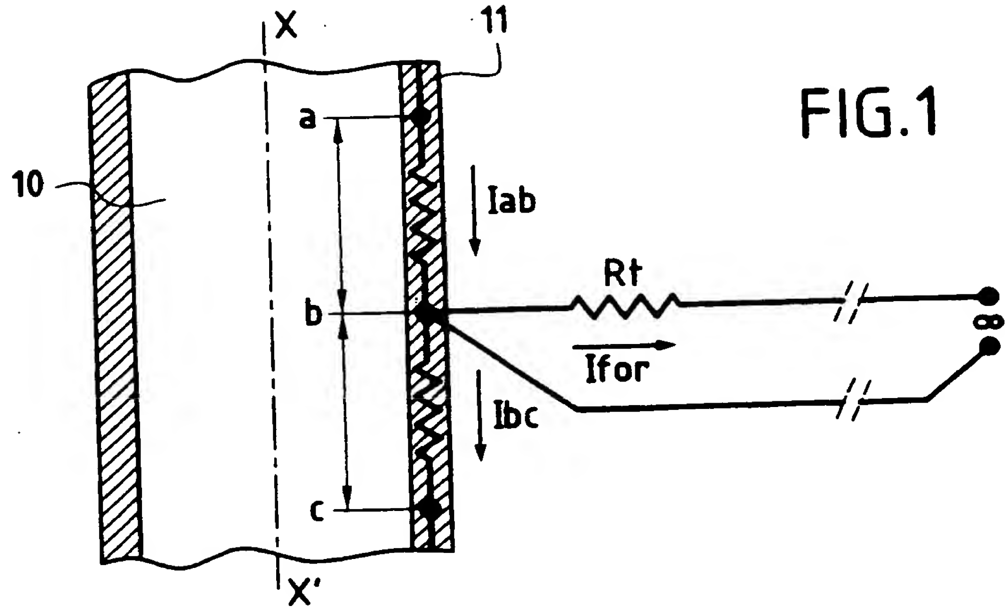
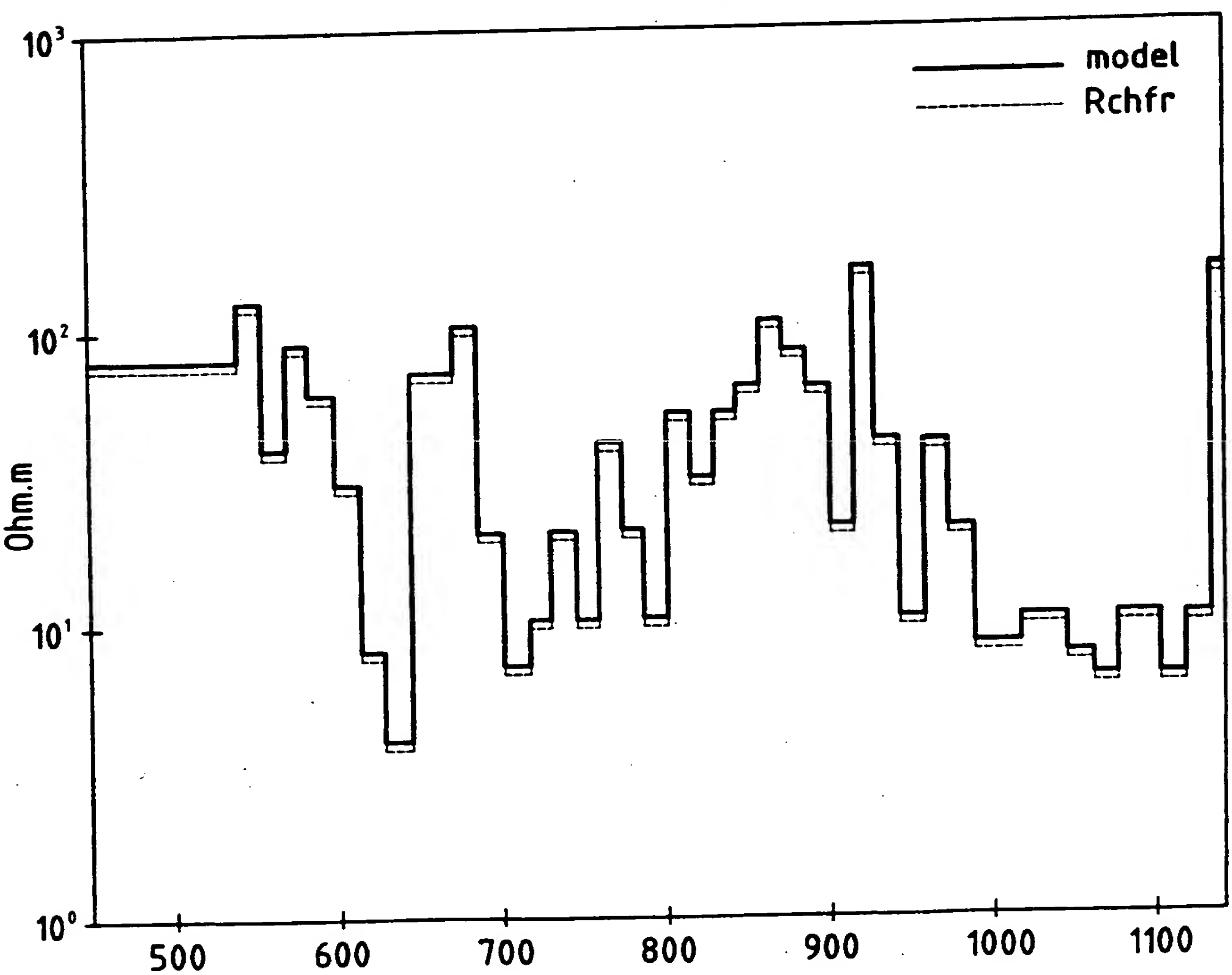

X
11
a
10
Iab
Rt
b
∞
Ifor
Ibc
c
X'

FIG.1

FIG.4


10³
model
Rchfr
10²
Ohm.m
10¹
10⁰
500
600
700
800
900
1000
1100

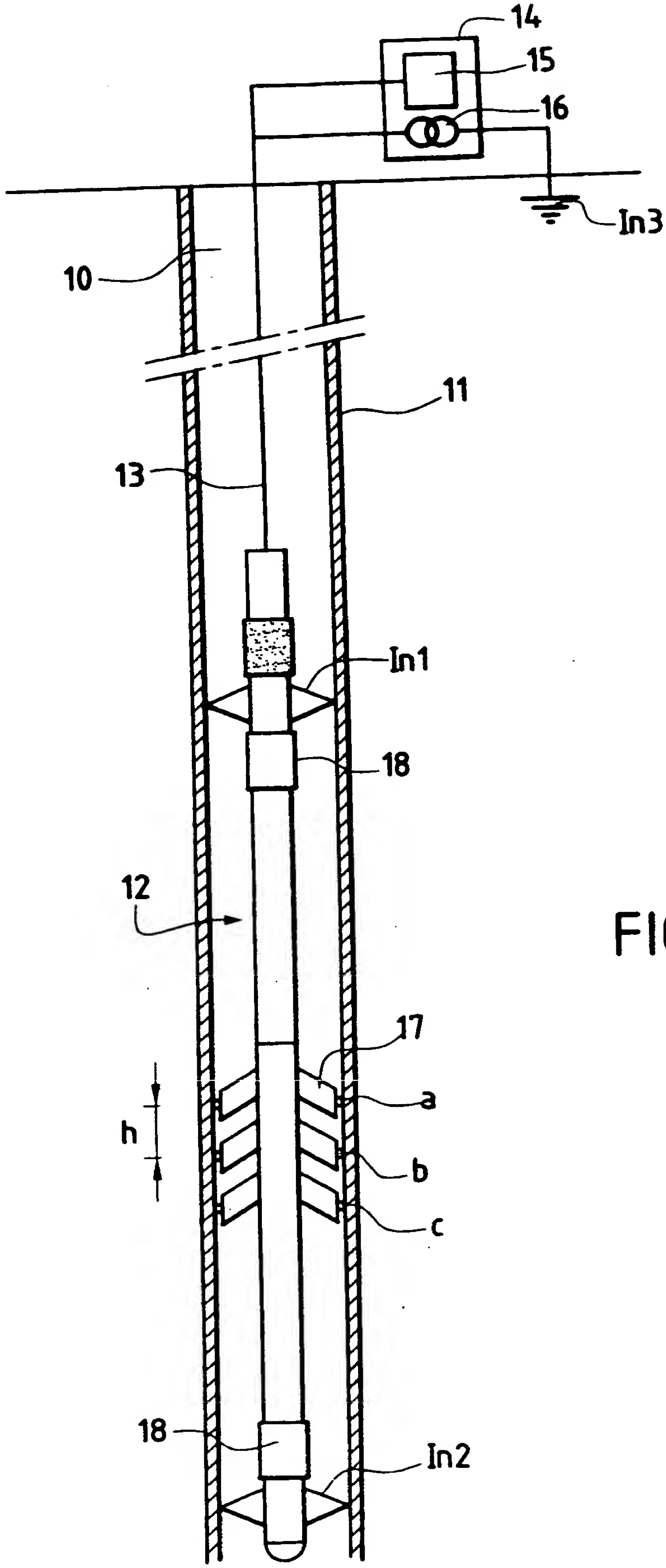


FIG.2

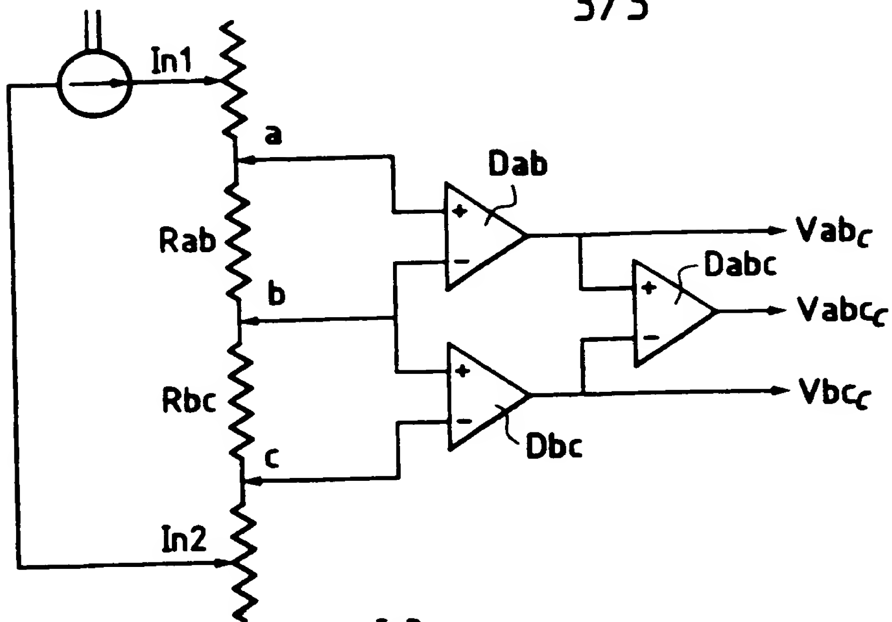


FIG.3A

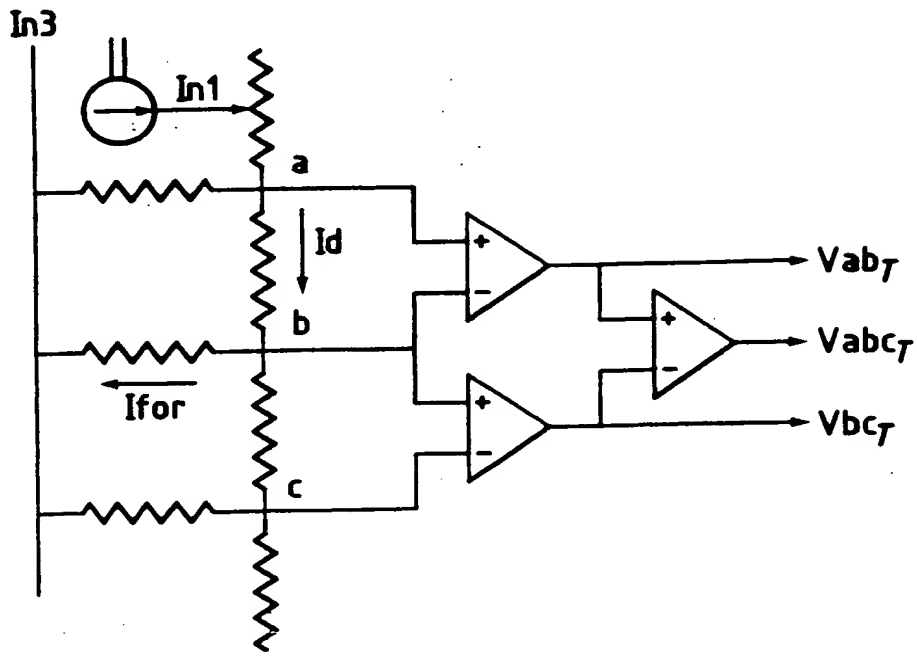


FIG.3B

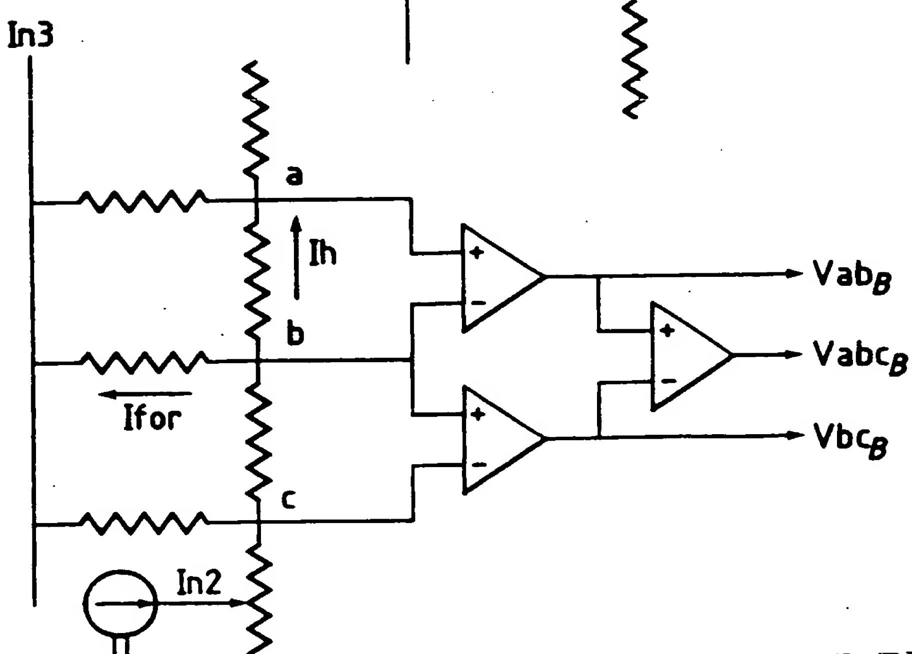


FIG.3C

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 00/03749

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01V3/24

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, COMPENDEX, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 478 409 A (SCHLUMBERGER LTD ;SCHLUMBERGER TECHNOLOGY BV (NL); SCHLUMBERGER HO) 1 April 1992 (1992-04-01) abstract page 4, column 4, line 1 -page 5, column 6, line 23; claim 1 ---	1
A	US 5 543 715 A (SINGER BENSION ET AL) 6 August 1996 (1996-08-06) cited in the application abstract column 6, line 25 -column 7, line 15; claim 1 ---	1

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
8 August 2000	17/08/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Lorne, B

1

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 00/03749

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 510 712 A (SEZGINER ABDURRAHMAN ET AL) 23 April 1996 (1996-04-23) cited in the application column 1, line 49 -column 2, line 32 column 5, line 17 -column 6, line 15	1,5
A	US 5 075 626 A (VAIL III WILLIAM B) 24 December 1991 (1991-12-24) abstract column 10, line 20 - line 36; claim 1	1

1

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT
Information on patent family members

International Application No
PCT/EP 00/03749

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0478409 A	01-04-1992	FR 2666661 A	13-03-1992
		AU 649714 B	02-06-1994
		AU 8380091 A	19-03-1992
		DE 69106647 D	23-02-1995
		DK 478409 T	19-06-1995
		NO 303251 B	15-06-1998
		US 5268641 A	07-12-1993
		ZA 9107221 A	27-05-1992
US 5543715 A	06-08-1996	CA 2185480 A	15-03-1997
		GB 2305249 A,B	02-04-1997
		NO 963663 A	17-03-1997
US 5510712 A	23-04-1996	FR 2719386 A	03-11-1995
		GB 2289340 A,B	15-11-1995
US 5075626 A	24-12-1991	US 4820989 A	11-04-1989
		US 5570024 A	29-10-1996
		US 5633590 A	27-05-1997
		US 5717334 A	10-02-1998
		US 6031381 A	29-02-2000
		US 6025721 A	15-02-2000
		US 5223794 A	29-06-1993
		AT 91798 T	15-08-1993
		CA 1278342 A	27-12-1990
		CA 2037563 A	06-09-1992
		DE 3786671 D	26-08-1993
		EP 0329709 A	30-08-1989
		MX 161569 A	06-11-1990
		WO 8803657 A	19-05-1988
		US 4882542 A	21-11-1989
		WO 9216859 A	01-10-1992
		US 5187440 A	16-02-1993